UNCLASSIFIED

AD NUMBER
AD035047
CLASSIFICATION CHANGES
TO: **unclassified**
FROM: **confidential**
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution: Further dissemination only as directed by Office of Naval Research, Attn: Code 466, One Liberty Center, 875 North Randolph Street, Arlington, VA 22203-1995, 30 JUN 1954, or higher DoD authority.**
AUTHORITY
30 Jun 1966, DoDD 5200.10; ONR ltr dtd 26 Oct 1977

THIS PAGE IS UNCLASSIFIED

45579

018

AD No. 35 040
ASTIA FILE COPY

SECRET

PROJECT MICHAEL

CONTRACT N6-ONR-27135

COLUMBIA UNIVERSITY

HUDSON LABORATORIES

DOBBS FERRY, N. Y.

RESEARCH SPONSORED BY

OFFICE OF NAVAL RESEARCH

CU-28-54-ONR-271-Phys

COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N. Y.

PROJECT MICHAEL

Contract N6-ONR-27135

Technical Report No. 21
A Progress Report in Shallow Water Research

by

W. A. Nierenberg, F. K. Levin
M. V. Brown and I. Tolstoy

W. A. Nierenberg
Director

Research Sponsored by
Office of Naval Research

Further distribution of this report, or of an abstract or reproductions, may be made only with the approval of Chief of Naval Research (Code 466).

Copy No. 048 | Confidential

of 60 copies | June 30, 1954

This report consists of 19 pages and an Appendix containing pages as noted on its title page.

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Sections 793 and 794. The transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

TAPLE OF CONTENTS

LIST OF ILLUSTRATIONS

SOUND DETECTION IN A WELL

* * *

RESPONSE PEAKING IN SHALLOW WATER TRANSMISSION

A PROGRESS REPORT IN SHALLOW WATER RESEARCH

INTRODUCTION

This is an introduction to the short note of Drs. Levin and Brown on preliminary results of some refraction shooting work performed at Panama City, and for the note of Dr. Tolstoy on CW propagation near the Virgin Islands. Complete reports on the work will be issued later but those special parts of the experiments which are purely exploratory are reported early because of their importance to the programming of research in the shallow water field.

The essence of the ideas involved are discussed in a special report[1] prepared by the Hudson Laboratories last November. In that report, the general status of the situation concerning the shallow water program was reviewed. It was suggested that new approaches to the problem were desirable and two such approaches were outlined. This report is, in essence, a progress report on these ideas as of this time. The remainder of this introduction treats these subjects in each of two separate paragraphs.

I. Well Hydrophones

Detailed studies of the theory involved in the propagation of low frequency (1-250 sec^{-1}) sound in shallow water show that the underlying geology plays a prominent part in the transmission of this sound. If the bottom consists of two or more well defined horizontal layers, it is conceivable that reception can be adequate in a deep well reaching through these layers even though the source is in the water. The essence of Brown's and Levin's results is that acoustic reception in a deep well on shore is about the same as for a hydrophone in the water at the same distance from the source. The distances involved in this preliminary experiment were of the order of two to three miles. Applying extraordinary optimism to the situation, one could predict that a series of 40 wells on Fire Island spaced approximately 25 feet apart in a straight line, the normal to which faces seaward, would

[1] Approaches to Studies of Shallow Water Sound Propagation, by I. Tolstoy, F. K. Levin, R. A. Frosch, and W. A. Nierenberg. Columbia University, Hudson Laboratories, Miscellaneous Report. December 10, 1953.

This Report did not receive wide circulation and is therefore appended to this Progress Report for convenience.

SECRET

give long ranges of shallow water detection. The output of the hydrophones in these wells would be fed into a delay line Lofar system similar to the Caesar system. In addition, since the wells could be 1000 ft deep, there may be room for 40 hydrophones on a string in each well, giving an additional factor of 40 in signal-to-noise. A suggested sequential program is the following:

1. Drill one well on Fire Island.

2. Measure the absolute intensity of received CW (say 30 ~) sound and explosive shots as a function of depth in the well for the closest possible distance.

3. Repeat as a function of range, to estimate the absorption.

4. Measure the relative phase of the received CW as a function of depth for the vertical array.

5. Drill a second well 1000 ft from the first on a line parallel to the shore.

6. Repeat all the earlier experiments with the second well.

7. Combine the output of the two to give a Corsair type test, i.e., "white light" fringes to check the coherency of the signal.

8. Fill in with 38 additional wells and check the signal-to-noise and signal vs range.

The advantages of such a system are obvious but are listed here anyway:

1. Eliminates the need for expensive armored cable.

2. Offers tremendous advantages in simplicity of design and maintenance.

3. It is invulnerable to attack by sneak submarines.

The proposed scheme may never be fully realized for any one or more of the following reasons as yet not understood:

1. The absorption in the underlying strata may be still too high at these frequencies.

2. The phase distribution in the vertical may be too complex for compensation.

3. The ambient noise may be too high.

4. In general, the geologic beds are not horizontal nor uniform. They often appear as wedges opening seaward. The present theory gives no clue as to the effect of this geometry.

It should be emphasized that even if such a system should have some degree of success in one area, it may not in another for the reasons enumerated.

II. Frequency Peaking

Another prediction of the theory in the low frequency region was the theorem that for CW propagation the acoustic excitation would vary approximately as the reciprocal of the group velocity for constant energy input. Since such a minimum generally does exist,this would imply a certain optimum frequency for low frequency acoustic mine sweeping.

The effect was looked for in experiments off the Virgin Isles and was demonstrated to exist. Dr. Tolstoy's preliminary report is included. The effect can be predicted with the knowledge of the velocities and densities of the underlying beds. However, since the Airy phase arrival is at essentially the same frequency, it would seem that a single shot judiciously disposed and analyzed would give some of the salient information required. This would reduce enormously the present program of harbor surveys with regard to low frequency sound transmission. Such a method would also be the only feasible one for "quick" surveys of harbors that political expediency would otherwise prevent.

W. A. Nierenberg
Director

WAN:fpr

SECRET

SOUND DETECTION IN A WELL

by

F. K. Levin and M. V. Brown

Introduction

Sound from charges detonated offshore was detected with a hydrophone in a well at Panama City, Florida, during the last two weeks of May, 1954. The investigation was incidental to the shooting of a reversed refraction profile in St. Andrew Bay and was conducted jointly by Hudson Laboratories and the U. S. Navy Mine Countermeasures Station. Although analysis of all data has not been completed, the preliminary results are considered worth reporting.

Fresh water for the Mine Countermeasures Station is supplied by two 600 foot wells.[1] Each well is 14 inches in diameter and has 200 feet of 12 inch casing. Samples taken during drilling of one of the wells gave the following geologic column:

0 - 40 feet	Sand
40 - 80 "	Loose Shell
80 - 210 "	Compressed Shell
210 - 600 "	Coral Rock

On May 19, 1954, one pump impeller was pulled and a hydrophone lowered into the well. At that time the water level stood at 39 feet below the surface. Reversed profiles with charges and hydrophone on the bottom were shot in St. Andrew Bay on May 20, 21 and 25, 1954. The shots were heard clearly on the well hydrophone and some of them were recorded on a six channel Brush oscillograph and on an Ampex magnetic tape recorder. The noise level in the well was high but during one particularly quiet period, an electrical cap detonated in the Bay more than three miles from the well was detected in the well. On May 26, 1954, Hudson Laboratories' twelve channel SIE oscillograph and associated equipment used in the refraction work was brought to the well site and on

[1] Information in this paragraph was furnished by Mr. J. W. Fairall of the U.S. Navy Mine Countermeasures Station in a private communication to the authors.

the following day records were taken with the hydrophone at 60, 150, 300, and 500 feet. Shot positions in St. Andrew Bay were 1.5, 1.8, 2.5, and 3.2 miles from the well. The shots were recorded simultaneously by Countermeasures Station scientists on Brush and Ampex units. Figure 1 shows the location of the well and of the two recording positions for the refraction profiles.

Results

The well records of May 27 were compared with refraction records taken on May 21 and 25, 1954. All records had three traces set at different gains which were fed through a low-pass filter. This filter nominally passed 60 cps down but the actual 0.9 point was closer to 30 cps.[2] Amplitudes of outstanding events were measured on the well records and on refraction records for the same source-detector separation (Figs. 2 - 5). The pressure level in dynes/cm^2 equivalent to one volt was furnished by the Mine Countermeasures Station from Ampex data. Amplitudes were reduced to those from one pount of TNT with the usual pressure ($p \propto W^{1/3}$) law. Since the sensitivities of the SIE galvanometers were unknown, amplitudes were compared with an arbitrary standard. Table I presents the pertinent results. Figure 6 shows the same data in graphical form.

Figures 2 - 5 are tracings from the SIE oscillograph records. These selected channels were measured in setting up Table I. The top three traces were recorded on May 21 at the point designated YR in Fig. 1. "Radioed Shot" represents the explosion as received at the firing ship and radioed to YR. "YR Water Arrival" is the high frequency water-borne impulse received by a bottomed hydrophone at YR, the charge being fired in the bay on a line joining YR and Barge and at a distance equal to the separation of Well and YR in Fig. 2. "YR Ground Arrival" is the earth-borne signal in the 30 cycle low-pass band as received at YR. The "YR to Well" traces correspond to explosions at YR received at the well at 60, 150, 300, and 500 ft depths. A similar procedure was followed for firing points designated at C7, N6, and C5.

[2]Well traces from a 15-40 cps band-pass filter looked "cleaner" than those from the low-pass filter, but the 15-40 cps unit was not used in the refraction program.

TABLE I

Event	Shot No.	Charge in Equivalent lb TNT	Receiver Well	Receiver Water	Depth in Feet	Range Seconds at 5000 ft/sec	Range Naut. Miles	Period Sec	RMS Ampl. mm	Rel. db
Able 2	28	9.5		YR		1.76	1.44	.034	26+10db	203
" "	29	9.5		YR		1.84	1.51	.034	51.3+10db	203
" 3	30	9.5		Barge		1.71	1.40	.035	72.3+10db	201
" "	31	9.5		Barge		1.77	1.45	.036	63.9+10db	200
Baker 1	1	1/2	X		60	1.74	1.43	.035	31.5	202
" 1	2	1/2	X		150	1.74	1.43			
" "	3	1/2	X		300	1.74	1.43	.042	30.2	200
" "	4	1/2	X		500	1.74	1.43	.034	27.3	197
Able 2	33	9.5		YR		2.21	1.81	.036	43.1	191
" "	34	9.5		YR		2.27	1.86	.035	45.8	186
Baker 1	5	1	X		500	2.20	1.80	.036	12.2	190
" "	6	1	X		300	2.20	1.80	.039	22.8	195
" 1	7	1	X		150	2.20	1.80	.038	14.0	191
" 1	8	1	X		60	2.20	1.80	.032	15.2	192
Able 2	44	24.5		YR		3.03	2.48	.036	214	193
" 2	45	24.5		YR		3.11	2.55	.040	58.5	184
Baker 1	9	3 1/2	X		60	3.04	2.49	.033	22.6	192
" 1	10	3 1/2	X		150	3.04	2.49	.038	17.4	189
" 1	11	3 1/2	X		300	3.04	2.49	.042	18.4	190
" 1	12	3 1/2	X		500	3.04	2.49	.041	16.0	189
Able 2	53	24.5		YR		3.74	3.07	.043	45	186
" "	54	24.5		YR		3.82	3.14	.042	49.3	187
Baker 1	13	9.5	X		500	3.82	3.14	.034	14.4	186
" 1	14	9.5	X		300	3.82	3.14	.037	15.0	186
" 1	15	9.5	X		150	3.82	3.14			
" 1	16	9.5	X		60	3.82	3.14	.032	13.5	185

An examination of Table I leads to the following conclusions:

(1) Within the rather large experimental scatter, amplitudes of sound detected at all depths in the well are the same as those detected with a bottomed hydrophone at corresponding source-detector separations in the water.

(2) All measured events have about the same peak-to-peak period ($\sim$ 0.035 sec).

Several apparent velocities were found for events recorded in the well. (Table II) Time "picks" for velocity determinations were made mostly on later arrivals and, hence, are uncertain.

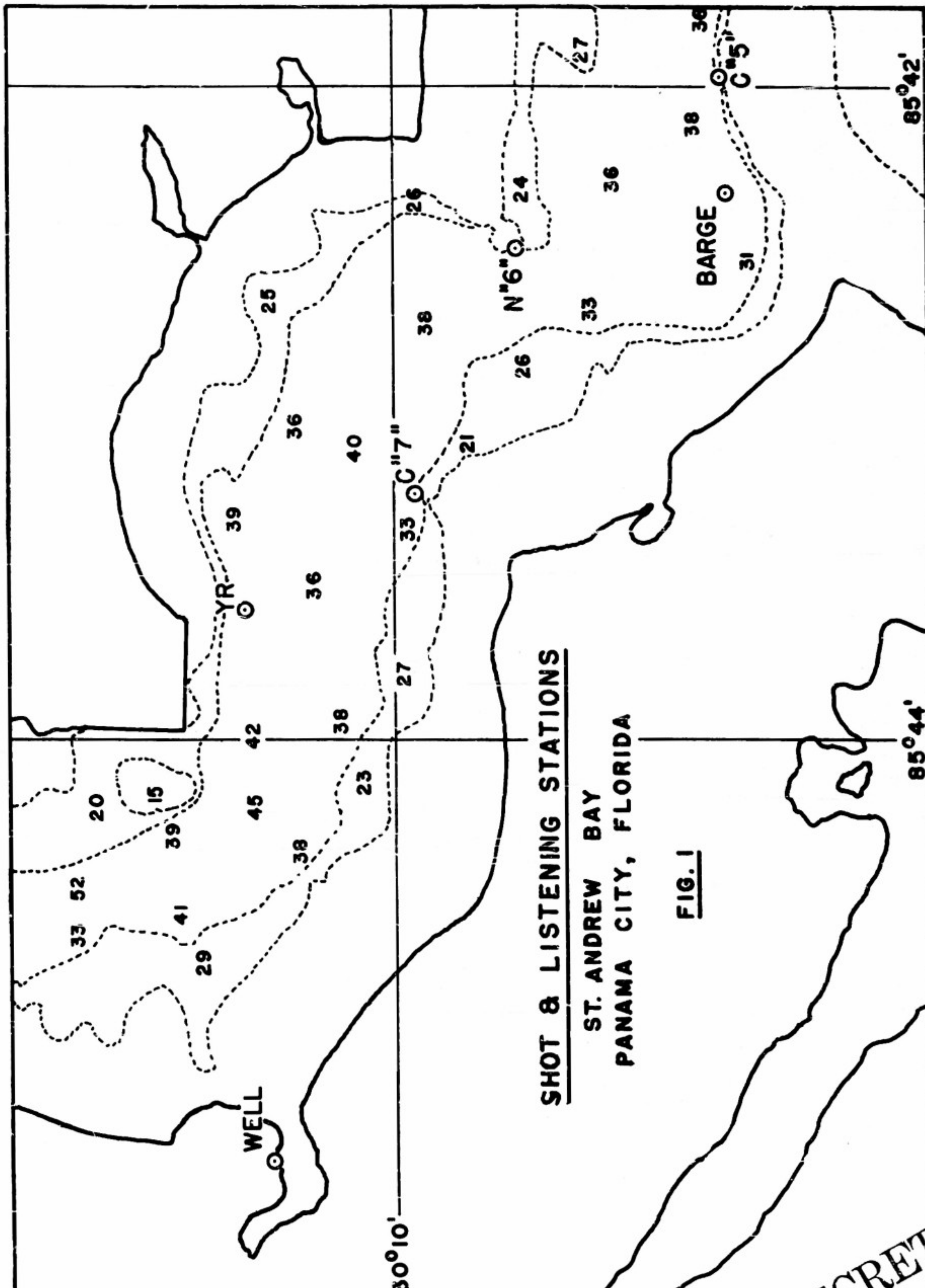
TABLE II

Depth of Hydrophone	Velocities in ft/sec
60 feet	6250, 7600
150 "	5700
300 "	6800, 8850
500 "	7200, 8850

Too much weight should not be assigned these values since the shot points were widely separated.

Preliminary analysis of the refraction data gave a subbottom consisting of 100 ft of 5300 ft/sec material, 200 ft of 6100 ft/sec material, a 500 ft layer with a velocity of 7300 ft/sec and a thick bed with a velocity of 8800 ft/sec.

The noise level in the well was much higher than that found in St. Andrew Bay. Part of the noise was 60 cps electrical pickup due to ground loops and aggravated by rain dripping through the well house roof onto the equipment. The greatest part of the noise seemed to be mechanical and was traced to nearby machinery. When the machinery was shut down, the noise level dropped. The noise level decreased markedly with increasing hydrophone depth (Figs. 2 - 5).

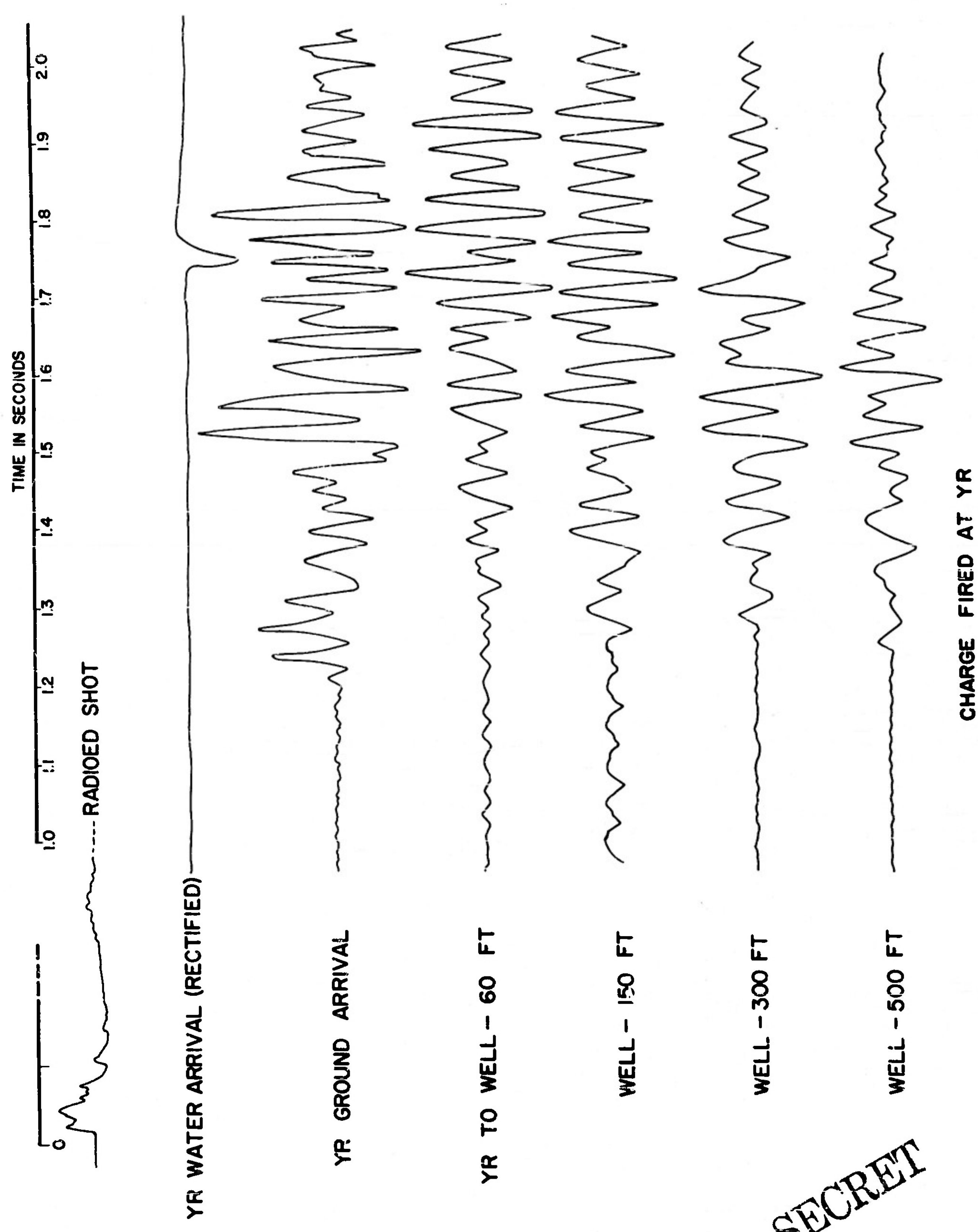


SHOT & LISTENING STATIONS

ST. ANDREW BAY

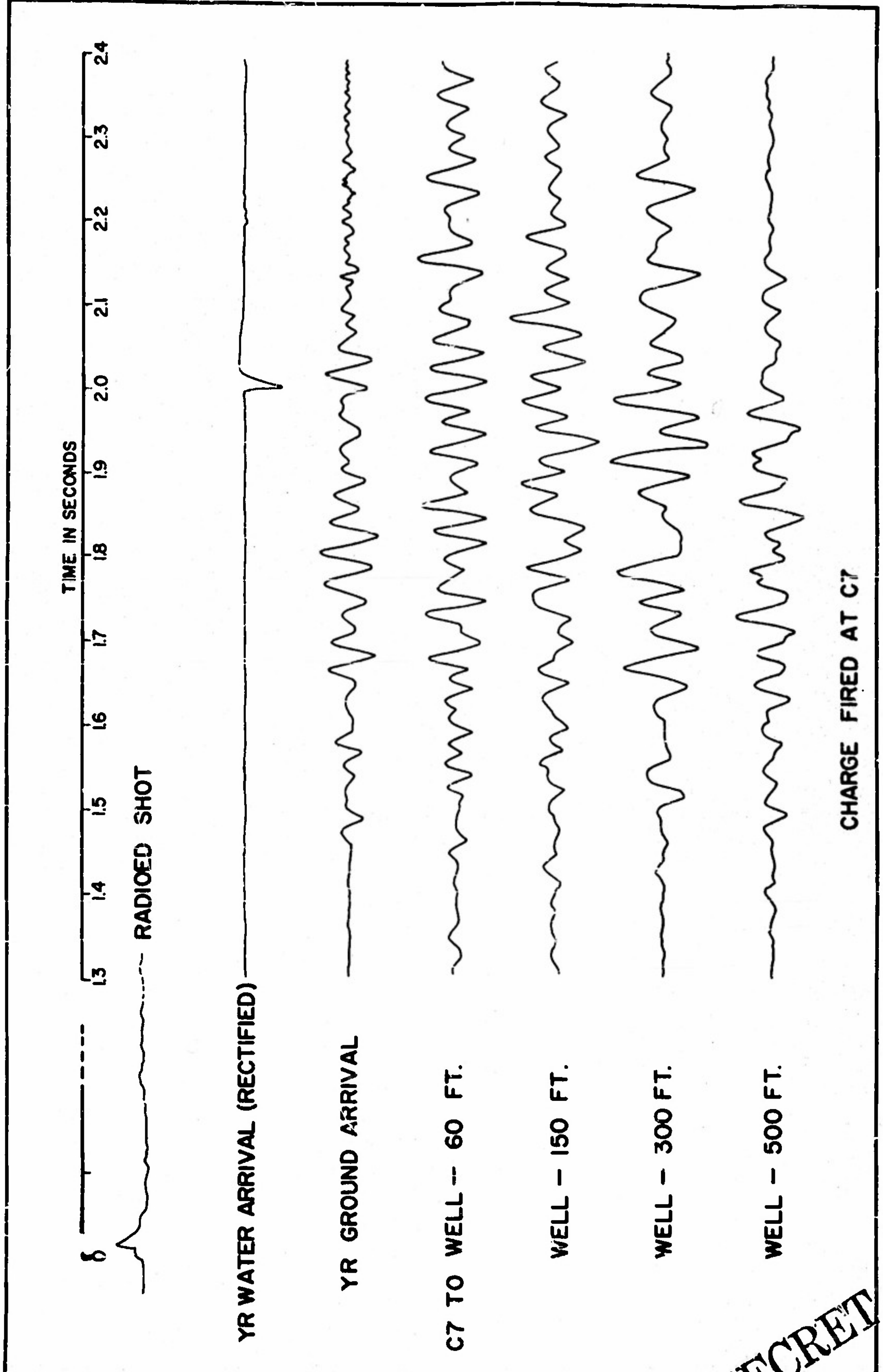
PANAMA CITY, FLORIDA

FIG. I


TIME IN SECONDS
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
RADIOED SHOT
0
YR WATER ARRIVAL (RECTIFIED)
YR GROUND ARRIVAL
YR TO WELL - 60 FT
WELL - 150 FT
WELL - 300 FT
WELL - 500 FT
CHARGE FIRED AT YR

SECRET

FIG. 2


TIME IN SECONDS
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
RADIOED SHOT
YR WATER ARRIVAL (RECTIFIED)
YR GROUND ARRIVAL
C7 TO WELL -- 60 FT.
WELL - 150 FT.
WELL - 300 FT.
WELL - 500 FT.
CHARGE FIRED AT C7

SECRET

FIG. 3

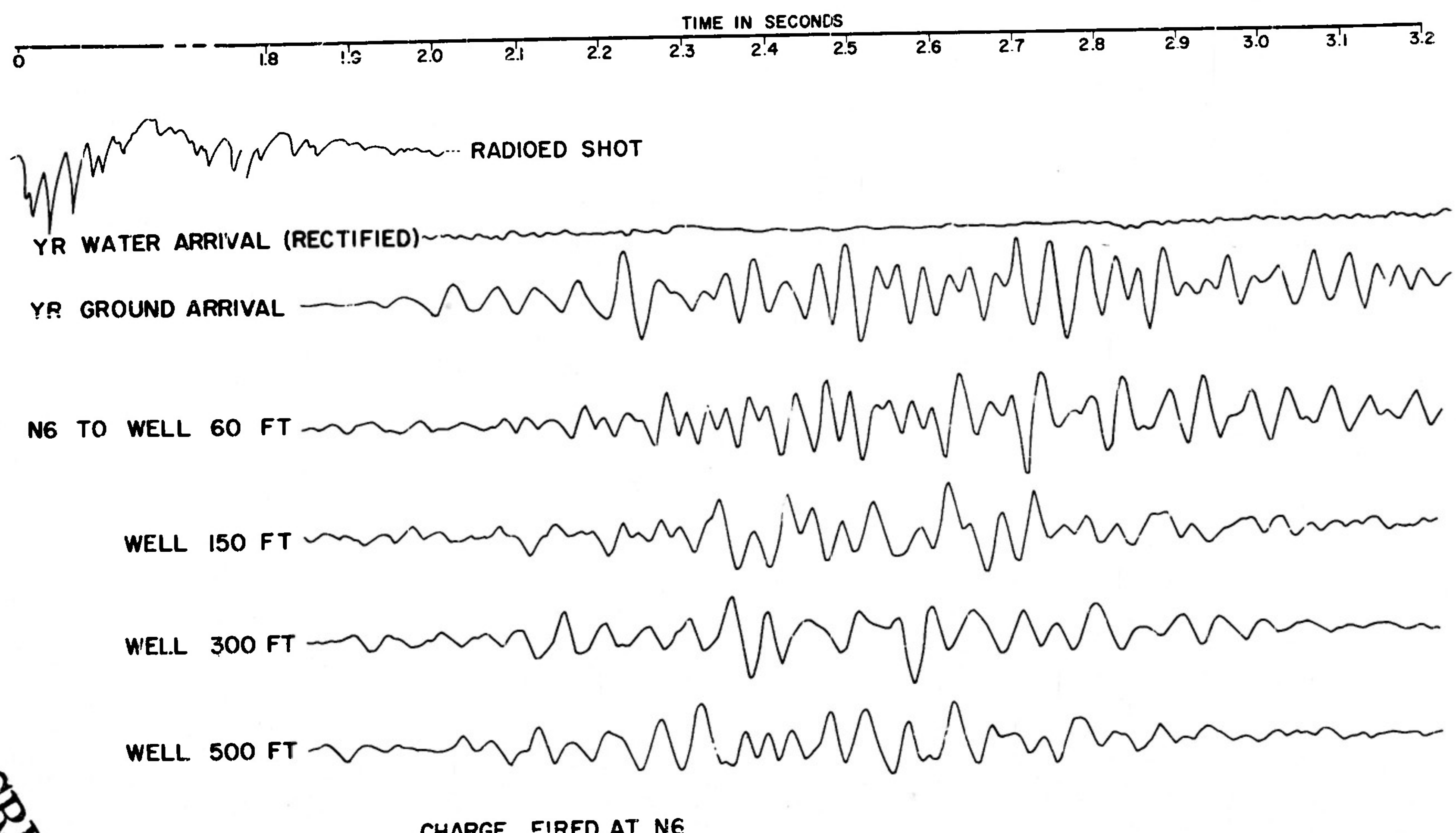

TIME IN SECONDS
0
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
RADIOED SHOT
YR WATER ARRIVAL (RECTIFIED)
YR GROUND ARRIVAL
N6 TO WELL 60 FT
WELL 150 FT
WELL 300 FT
WELL 500 FT
CHARGE FIRED AT N6

FIG. 4

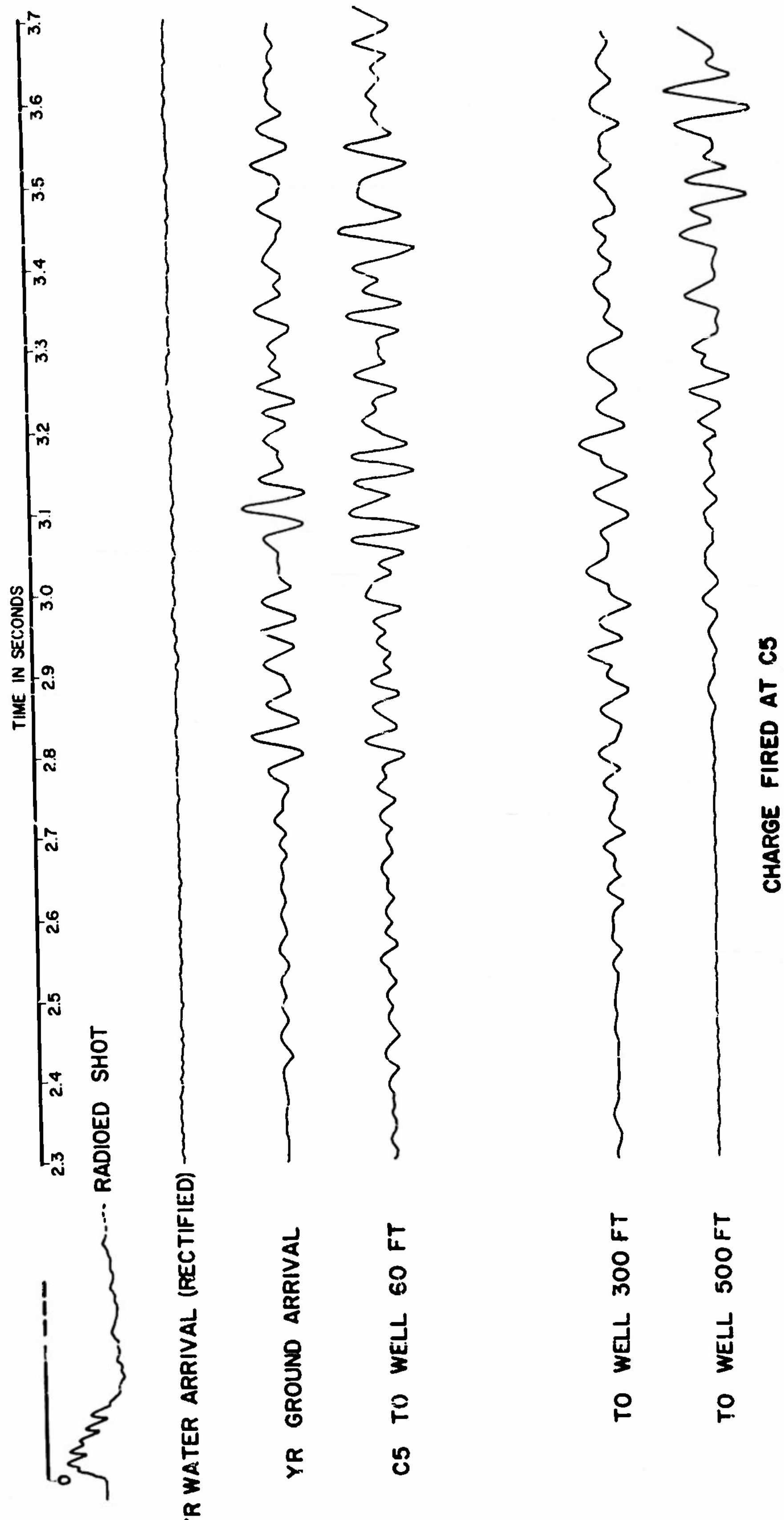

TIME IN SECONDS
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
3.4
3.5
3.6
3.7
0
RADIOED SHOT
YR WATER ARRIVAL (RECTIFIED)
YR GROUND ARRIVAL
C5 TO WELL 60 FT
TO WELL 300 FT
TO WELL 500 FT
CHARGE FIRED AT C5

FIG. 5

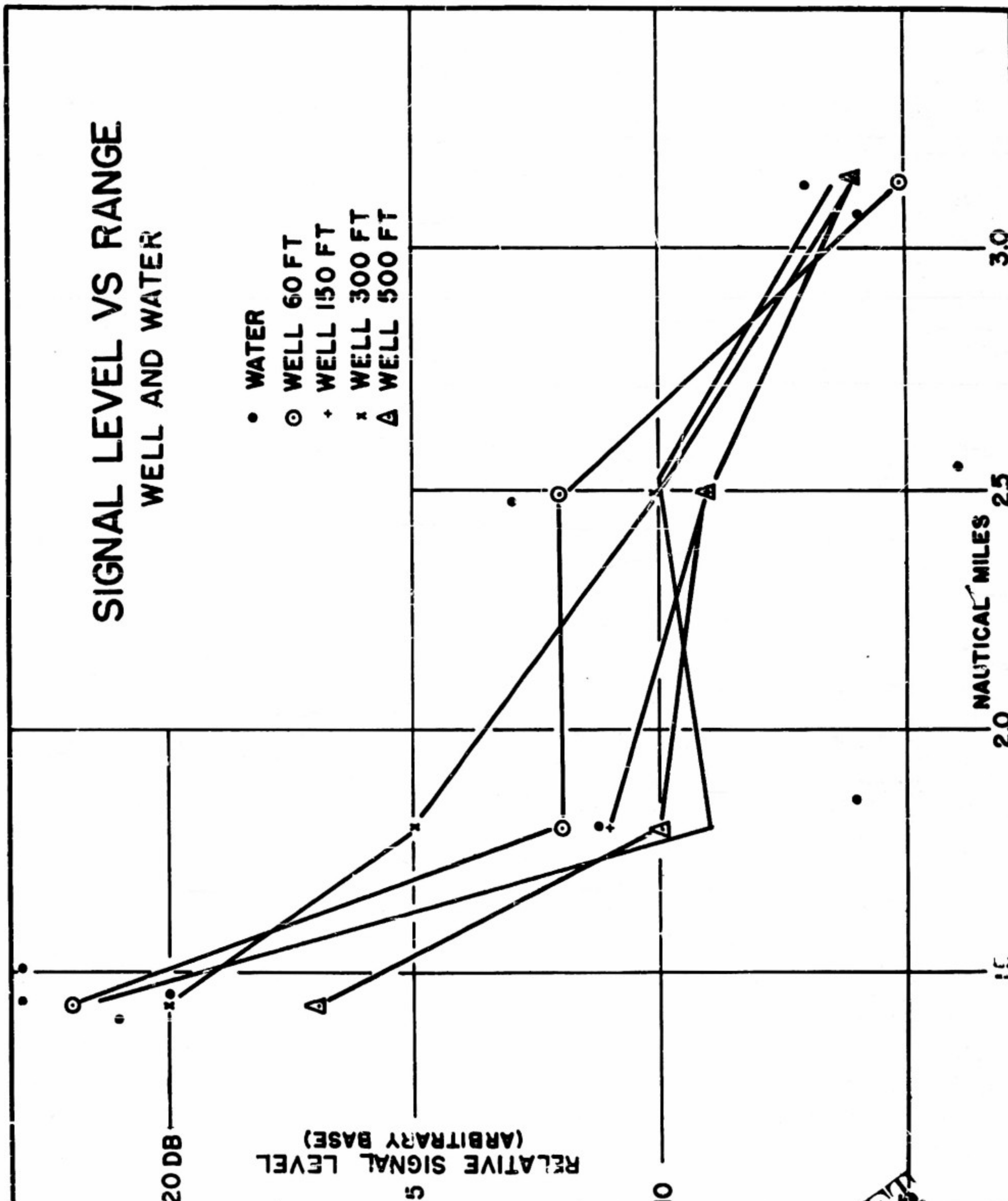

SIGNAL LEVEL VS RANGE
WELL AND WATER
• WATER
⊙ WELL 60 FT
+ WELL 150 FT
× WELL 300 FT
Δ WELL 500 FT
RELATIVE SIGNAL LEVEL
(ARBITRARY BASE)
20 DB
15
10
1.5
2.0
2.5
3.0
NAUTICAL MILES

FIG. 6

RESPONSE PEAKING IN SHALLOW WATER TRANSMISSION

by

I. Tolstoy

The prediction of a peak CW response for frequencies close to the Airy frequency was verified by CW experiments in St.Thomas, V.I., conducted at the beginning of February, 1954. This result is illustrated by the following comparisons of pressure levels for different frequencies along neighboring tracks:

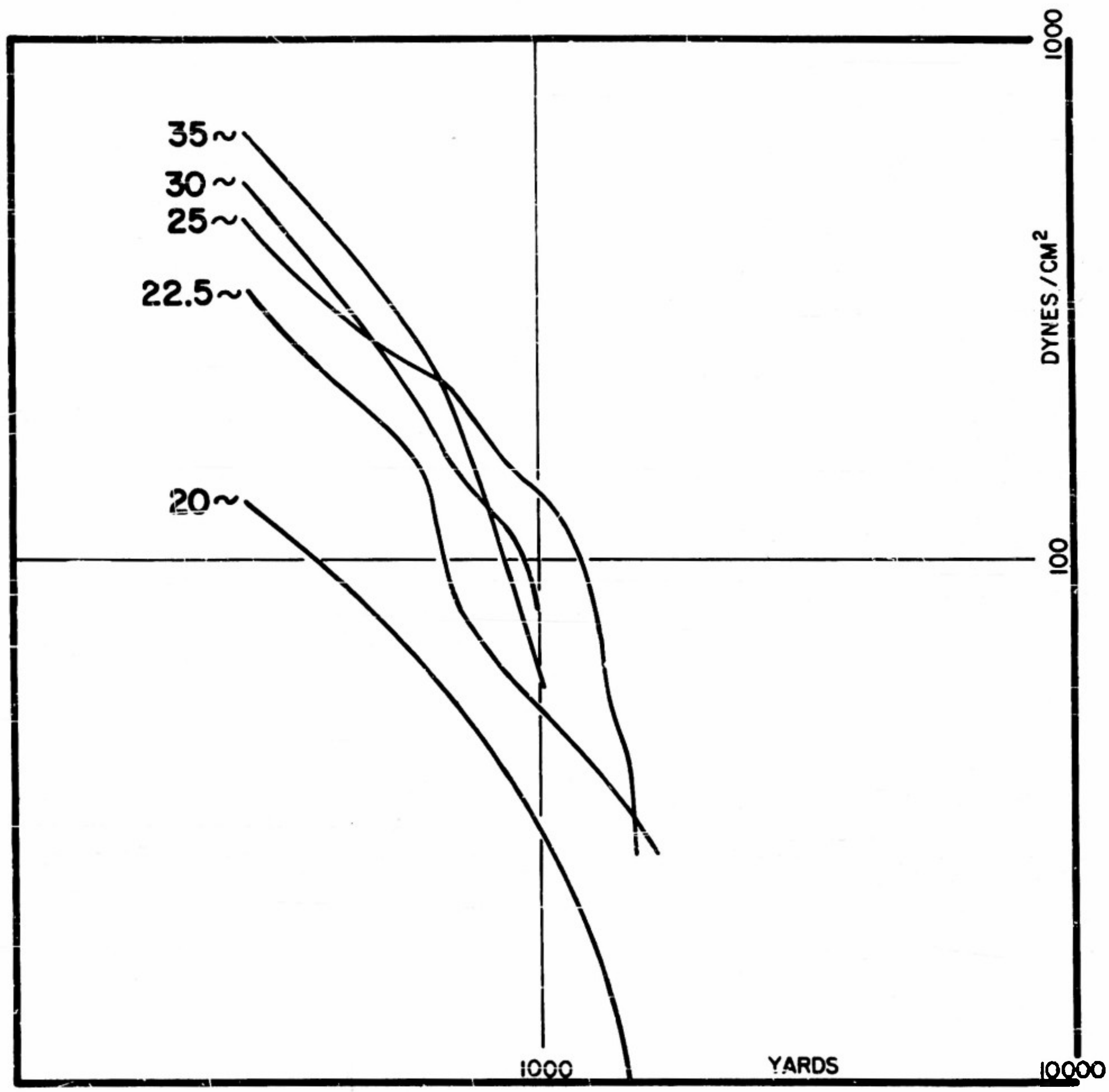
a) A plot on log-log paper of the pressure vs range curves. (Fig. 1).

b) Pressure levels for different frequencies at 1250, 1000, and 750 yards from the source were averaged to eliminate local effects insofar as possible (Fig. 2).

Figure 2 shows a pronounced peak at about 25 cps, which is effectively very close to the Airy phase frequency as determined from shot data ($\sim$ 21 cps). This is the predicted resonance effect. However, the phenomenon appears to be considerably sharper than that predicted on the basis of any reasonable theoretical model. The cause for this sharpening is unknown at present. It could be due to a combination of topographic and structural effects.

Figure 1 shows that had we used some process of averaging which would include the whole run from, say, 100 to 1500 yards, the peak shown by Fig. 2 could have been flattened.

Both refraction and submarine topography surveys in this location showed the bottom to be far from ideal for the purposes of our experiment. Marked local departures from predictions based upon any crude average picture deduced from refraction data are therefore to be expected.



COMPARISON OF PRESSURE VS RANGE CURVES ALONG NEIGHBORING TRACKS FOR DIFFERENT FREQUENCIES

FIG. 1

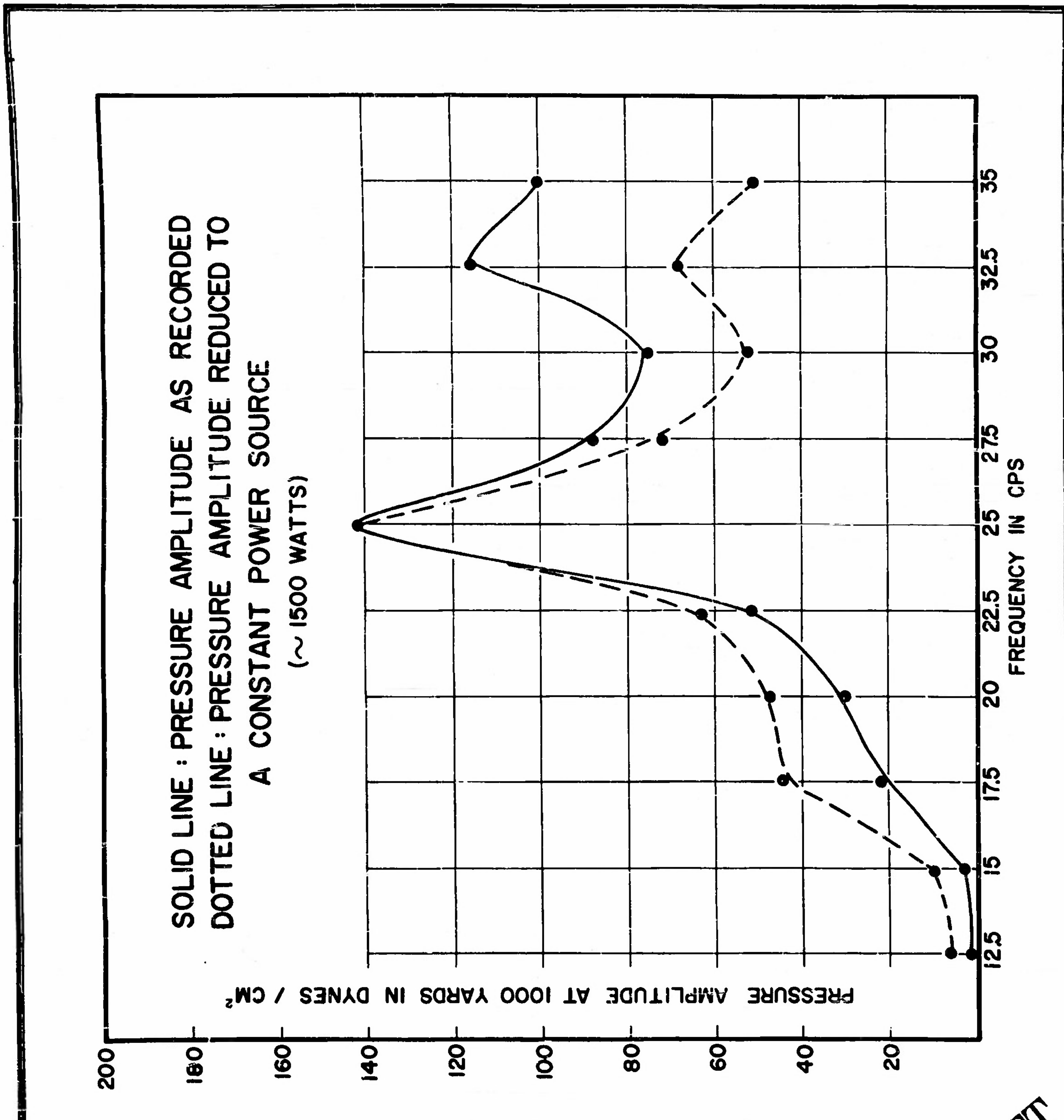

SOLID LINE : PRESSURE AMPLITUDE AS RECORDED
DOTTED LINE : PRESSURE AMPLITUDE REDUCED TO
A CONSTANT POWER SOURCE
(~ 1500 WATTS)
PRESSURE AMPLITUDE AT 1000 YARDS IN DYNES / CM²
200
180
160
140
120
100
80
60
40
20
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
FREQUENCY IN CPS

FIG. 2

COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N. Y.

PROJECT MICHAEL

Contract N6-ONR-27135

APPROACHES TO STUDIES OF SHALLOW WATER SOUND PROPAGATION

W. A. Nierenberg

Director

Research Sponsored by
Office of Naval Research

CONFIDENTIAL — December 10, 1953

SECURITY INFORMATION — Copy No.

This report consists of 4 prefatory pages and additional pages, as noted in Contents

CONTENTS

INTRODUCTION

The enclosed memoranda form a series of comments by members of the Hudson Laboratories with regard to possible directions of research in shallow water sound propagation in those areas where ray tracing is either too cumbersome or neglects wave effects to an extreme. These memoranda have been assembled for convenience.

A cursory examination of the problem reveals it to be not one of equipments, but situations. The maximum use of given equipment will vary widely from site to site, perhaps to the extent that widely different frequency bands must be utilized both for passive and active listening.

From this viewpoint, these memoranda achieve three results. They suggest definitive experimental procedures which limit the research to amassing the data that will be necessary for defense. They suggest definite experimental procedures that are required for the identification of acoustically similar areas. Finally, they suggest several new approaches to the problem of shallow water listening and active ranging that derive from the theory.

As examples of the value of these memoranda, we would like to employ this space to re-emphasize two of the new approaches. In a situation where the water is underlaid by parallel layers of increasing velocity sediments and rock, the theory is sufficiently good to estimate the variation of the group velocities with frequency. Since the C.W. excitation for constant energy input varies inversely as the group velocity, we expect

a maximum excitation for a minimum of the group velocity curve of any mode, and vice versa. These maxima can in themselves be useful and they also indicate the distortion that would be present in a given spectrum. In the same situation we may find that a cut-off frequency for a given depth of water may not be cut-off when an intermediate rock layer is considered. Consequently, a listening device in a narrow bore reaching to the center of this layer may give enhanced reception.

The contents of these memoranda were discussed by their authors before an interested group in the Department of the Navy on November 25, 1953.

W. A. Nierenberg
W. A. Nierenberg
Director
Contract N6-ONR-27135

CONFIDENTIAL COLUMBIA UNIVERSITY #13

SECRET Interdepartment Memorandum

Date: October 19, 1953

To: Dr. W. A. Nierenberg

From: Dr. Ivan Tolstoy

Subject: Sound Propagation, Shallow Water Locations

The following are a few suggestions for remedying the largest and most obvious gaps in our knowledge concerning sound propagation in strategic shallow water locations (such as the vicinity and interior of harbors).

C.W. work was carried out in the vicinity of Ambrose Light in conjunction with a refraction profile. The results obtained were in rough agreement with Pekeris' shallow water theory. In other words, it is plausible to assume that in order to understand low frequency sound propagation in the case of approximately smooth and horizontal bottom structure, what will mostly be required will be some additional numerical and theoretical work along similar lines. However, the Ambrose Light experiments represent the only C.W. work that has been carried out successfully in conjunction with a knowledge of bottom structure.

Present day knowledge of bottom structure in shallow water is insufficient to enable us even to classify by type the major harbor areas of the world, let alone to predict the properties of low frequency sound propagation in these areas.

A very rough classification by bottom type is perhaps possible for a few locations, mostly along the East Coast of the United States. Even in these places (Boston, Portsmouth, the entrances to the Delaware and Chesapeake Bays), it will be necessary to carry out refraction measurements at each C.W. location before interpretation of such work can be made with assurance. The data for these areas are due primarily to staff members, present and past, of what is today the Lamont Geological Observatory. By means of some rather gross extrapolation and interpolation of their results, we have arrived at the following picture of some shallow water types in areas of interest:

<u>Newfoundland Coast, south of Placentia Bay</u> - Unconsolidated sediments are thin (500 ft thick, velocity 5300 ft/sec). They overlie a 6000 ft layer of 14,500 ft/sec rock.

CONFIDENTIAL
SECURITY INFORMATION

SECRET

Portsmouth, Maine - Sediments very thin (a few hundred feet at most) perhaps absent. "Basement" velocity 17-18,000 ft/sec.

Boston, Massachusetts - Similar to Portsmouth. (Interpolated between Woods Hole and Gulf of Maine data.) Peculiar bottom topography features (deep holes of over 200 ft depth).

New York area - Good data at Ambrose Light. Oliver and Drake's profiles south of Block Island and Shinnecock are very similar, indicating a reasonable degree of predictability of bottom conditions in this general area. It appears that there is a layer of 5600-5900 ft/sec "unconsolidated" sediment (400-750 ft thick) over a 6400-6900 ft/sec sediment (1000-2000 ft thick) over a basement of about 19,000 ft/sec velocity.

Delaware entrance - The Cape May profiles give a 5500 ft/sec layer (2000 ft thick) overlying very thick sediments of 10,800 ft/sec velocity. It is possible that a more detailed profile would show layering in the 5600 ft/sec layer. In other words, the velocity cross-section of the upper 2000 ft is not necessarily too different from that of the New York area.

Chesapeake Bay - The Cape Henry profiles show a layering near the entrance to the Bay analogous to the New York area: a layer of 5550 ft/sec (1600 ft thick) over a 7350 ft/sec sediment (1300 ft thick) over a 17,500 ft/sec basement. The Solomons shoal and deep stations within the Bay yielded different results: the shoal station gives 3000 ft of 5900 ft/sec over 15,200 ft/sec basement (in 52 ft of water) whereas the deep station gives 1000 ft of 6080 ft/sec over 1800 ft of 6980 ft/sec over a 18,000 ft/sec basement (in 110 ft of water). These two profiles were not reversed so that there is considerable room for interpretation of the data.

West Indies - Lines suggest that here too the shallow water sediments consist of a 5600 ft/sec layer over thick high velocity sediments.

Recife, Brazil - Offshore from Recife unpublished Lamont Geological Observatory data indicate in 50 ft of water, 5000 ft of roughly 11,000 ft/sec coral limestone overlying 19-20,000 ft/sec basement. There appear to be almost no unconsolidated sediments.

Dakar, A.O.F. - Unpublished Lamont data indicate a very great thickness of unconsolidated sediments (more than 4500 ft thick), the velocity of which varies apparently from normal (5600 ft/sec) to less than the speed of sound in water.

Bermuda - High velocity rough coral limestone bottom (> 13,000 ft/sec) with practically no sedimentary cover.

This brief and incomplete summary of existing data shows that a C.W. survey will have to be carried out in conjunction with a refraction profile and a fathometer survey for each location. Furthermore, it is not possible today to conclude anything about shallow water propagation in any areas in which actual experiments have not been carried out. The first steps towards an overall understanding of shallow water sound conditions the world over may be conceived as follows: starting with approximately smooth and horizontal bottom conditions -

a) Investigate the locations that appear roughly similar to us today: the New York area, and the entrance to the Chesapeake and Delaware Bays, and ascertain whether or not the relatively small differences in type have important effects upon l.f. sound propagation. Naturally, such differences will have to be correlated with the theory before we would feel confident in making forecasts for unexplored areas of similar type.

b) Investigate locations that we know to be of radically different type from the above, such as Portsmouth and Boston Harbor areas. Here the sediment is very thin and perhaps non-existent in many places, so that solid bottom theory will have to be used. As for rough bottoms, they will often be rocky - Bermuda is an example (St. George's and Hamilton Harbors and the narrow shallow water shelf). Sloping bottom studies should, of course, be carried out in locations where the velocity sections are known.

Such C. W. experiments must, of course, be paralleled by the compilation of all available geological and topographical data. Information about velocity cross-sections in shallow water seems to be very sparse. It is needless to stress the critical and unique importance of obtaining this data. The necessity of doing considerable refraction work in and near areas of strategic interest is therefore obvious. With any kind of launch-ship combination a reversed refraction profile can be successfully completed in one day. It is therefore feasible to obtain velocity cross-section sampling at a rather goodly rate. Even the acquisition of twenty or thirty cross-sections in various areas around the world would be a great help. The existence of such data is a sine-qua-non for the success of any comprehensive C.W. program. It appears, therefore, that a shallow water refraction profile program should be set up as a separate unit to complement the C. W. research.

The question naturally arises as to whether this program is to be limited to short profiles which would just give us the detail of the upper few Km or to longer ones giving us the whole cross-section up to, say, 20 Km. The arguments in favor of long profiles are:

a) The deep "refracted waves" may be, in many cases, of considerable practical interest, since they represent the first arrival at large distances.

b) The amount of additional time required to lengthen a profile is negligible compared to the time and labor involved in all the operations attendant upon setting up such an experiment, as for example, assembling equipment, personnel, vessels, and bringing them to a given location. I, therefore, feel that this course is to be recommended, providing that the close-in shots be not neglected in favor of the distant ones.

When sufficient confidence in our interpretation of C. W. work will have been achieved, it is reasonable to expect that given the velocity cross-section in a given area (or a good guess for it) it will be possible to forecast the shallow water sound conditions with a good measure of success.

CONFIDENTIAL SECRET

COLUMBIA UNIVERSITY
Interdepartment Memorandum

#14

Date: October 20, 1953

To: Dr. W.A. Nierenberg

From: Dr. Ivan Tolstoy

Subject: Shallow Water Program

This gives an outline of some ideas concerning the shallow water program. It will be noted that the last two items mentioned are also applicable to deep-water work.

The suggestions made here are, broadly speaking, of three types:

A. Those dealing with experiments that can be usefully performed at the present time without preliminary numerical or theoretical work.

B. Those pertaining to experiments, the exact specification and usefulness of which will depend upon the availability of numerical data, which although not necessarily available today can be readily obtained from extant theory.

C. Those pertaining to experiments, the specification of which is contingent upon the conclusion of theoretical work now in progress.

Under (A) we would have the continuation and expansion of the C.W. work, in the fashion described in Memorandum #13. In other words, C. W. work may be usefully produced in conjunction with refraction profiles and fathometer surveys in order to determine empirically the effect of bottom geology upon low frequency sound propagation.

Under heading (B) would come:

1. Establishing a correlation between the experimental results of the aforementioned C.W. work and the Pekeris "shallow water theory" whenever possible. This would involve numerical calculations based upon Pekeris' or similar formulae and applied to the bottom structure as determined by the refraction profiles.

2. This last suggestion could be considered as a step towards, or as an integral part of, a more general numerical program involving the tabulation of some of the theoretically simpler features of shallow water theory. Examples of

CONFIDENTIAL SECRET
SECURITY INFORMATION

these are the dispersion curves for the normal modes and the distribution of maxima and minima of functions of the type $H_0 (k_n r)$ determining the normal mode amplitudes as a function of range (k_n is the wave number of the n^{th} mode, r the horizontal radial distance from the source).

3. A consequence of this numerical study would be to predict the frequencies associated with stationary values of the group velocity in a given location. The theory of undamped normal mode propagation predicts that transmission would be most efficient for these frequencies. It is important to determine whether this fact can be exploited for C.W. transmission.

4. It is quite certain that solid bottom theory will have to be used in locations for which the sedimentary cover is thin or negligible (Portsmouth, Boston Harbor, Bermuda, are possible examples of this).

Under (C) we would include:

1. Determination of frequencies of minimum reverberation and most efficient transmission of high frequency sound, both in stratified media and in media with continuous velocity and density gradients.

2. Determination of the dispersive properties of normal modes in media involving many layers, with or without continuous gradations of properties. As an example, this would include the determination of the normal modes of the Sofar channel.

These are just two possibilities that have suggested themselves to us under heading (C) as consequences of a theory of sound propagation in inhomogeneous media that will be put into usable form during the next two months, and are contingent upon the feasibility of a moderately large computing program based upon it.

COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N.Y.

PROJECT MICHAEL

Contract N6-ONR-27135

Technical Memorandum to File No. 9

THE USE OF MODELS IN SHALLOW WATER SOUND PROPAGATION STUDIES

By
F. K. Levin

W.A. Nierenberg
Director

Research Sponsored by

Office of Naval Research

Further distribution of this report, or of an abstract or reproductions may be made only with the approval of Chief of Naval Research (Code 466).

CONFIDENTIAL November 13, 1953

SECURITY INFORMATION Copy No.

THE USE OF MODELS IN SHALLOW WATER SOUND PROPAGATION STUDIES

By

F. K. Levin

The phenomena involved in low frequency sound propagation through shallow water are inherently quite complex. It has been found experimentally at two locations that the sound amplitude from a single frequency source goes through numerous maxima and minima with increasing source-detector separation. Explanations of the sound intensity patterns have been sought in the "normal-mode" theory of Pekeris and others; in general, the agreement between theoretically predicted and experimentally measured results has been very satisfactory.

On the basis of the experimental work done thus far, it is felt that the normal-mode theory can predict sound propagation expected in the shallow water at a given place if the physical properties of the water and bottom are known and if the bottom and subbottom consist of few relatively thick, flat layers. In its present form, the theory can handle several liquid layers over a flat, solid layer; many locations of interest to the Navy can be represented very well by a section of this type. There are, however, other areas which cannot be described simply as water over a flat, infinitely thick solid bed. Either the bottom slopes or there are several underlying beds or both. To predict the sound amplitude-distance behavior for such areas requires a mathematical computer. A particularly simple computer is an analogue computer or model.

An analogue computer (model) solves problems of this type by

representing on a reduced scale sound propagating in the water and bottom. A convenient scale is a thousand feet of actual water and bottom to one foot of model: 100' of water becomes 1.2" in the model and a distance of 1000 yds. on location corresponds to 1 yd. in the model. If the liquid and solids used in the model have the same velocities (and densities) as those encountered at the location of interest, reducing the dimensions by a factor of a thousand requires increasing the frequencies by the same factor if the wave length to water thickness ratio is to remain unchanged. Field frequencies of 10 to 1000 cycles/sec. become model frequencies of 10 to 1000 kilocycles/sec. values extending well into the ultrasonic range. Techniques and equipment useful in this range are well developed, since ultrasonic models are in operation at several petroleum companies' laboratories and at universities. As a rough estimate, equipment required to generate and detect ultrasonic waves would cost less than $5000, exclusive of manpower -- which should not represent more than an additional $1000 -- to build special components. The model itself would be inexpensive, for the logical materials are cement and water or oil. Thus for a cost estimated generously as $10,000, an analogue computer capable of predicting the shallow water sound propagation in situations too complex for computation could be put into operation.

It is reasonable to ask if the results from a model would be the same as those produced by a solution of the corresponding mathematical equations.

Fortunately, there are available now reports of two experiments which indicate that the agreement between model results and mathematical predictions is very good indeed. At the Institute of Geophysics Technical Conference, UCLA, November 4 and 5, 1953, scientists from the Shell and Standard oil companies described work with ultrasonic models at their laboratories. The Stanolind experiment represented a direct check of the Pekeris liquid-over-liquid theory: the record from the model was nearly identical with the theoretically predicted wave complex, even minor details being reproduced. The Shell model consisted of a shallow water layer over concrete. Here only group velocity curves were shown but again the experimental points fell exactly on the theoretical plots. In view of the remarkable confirmation of normal-mode theories by model results for two simple configurations, it is felt that an ultrasonic model can be used to predict sound propagation for cases which can not now be treated theoretically.

Although the overall possibilities of aiding field operations with model experiments are good, there are several forseeable difficulties that should be mentioned. First, a model to represent an extended shallow water area on a scale of a thousand to one would be impracticably large. Second, in the same vein, a model once constructed would not likely be flexible and a new model would have to be constructed to represent a new situation. This would not limit the associated equipment which could be used with all models

In any case, models would not be expected to be expensive. Third, there would be little chance of scaling the sound source and detector, although, if the Shell and Stanolind results are typical, oversized sources and detectors would introduce no error. Finally, it is not now known how details of the bottom affect shallow water sound propagation. It certainly would not be easy to represent small bottom features in the model. The question of attenuation of sound in certain bottoms may be considered; however, nothing can be said at present, since the absorption properties of bottom materials are unknown.

COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N.Y.

Project Michael

Contract N6-ONR-27135

Technical Memorandum to File No.10

RESONANT FREQUENCIES IN SHALLOW WATER SOUND PROPAGATION AND OTHER SUGGESTIONS CONCERNING THE SHALLOW WATER PROGRAM

By I. Tolstoy

W.A. Nierenberg
Director

Research Sponsored by

Office of Naval Research

CONFIDENTIAL SECRET | November 17, 1953
SECURITY INFORMATION | Copy No.

TABLE OF CONTENTS

Resonant Frequencies in Shallow Water Sound Propagation and Other Suggestions Concerning the Shallow Water Program

By

Ivan Tolstoy

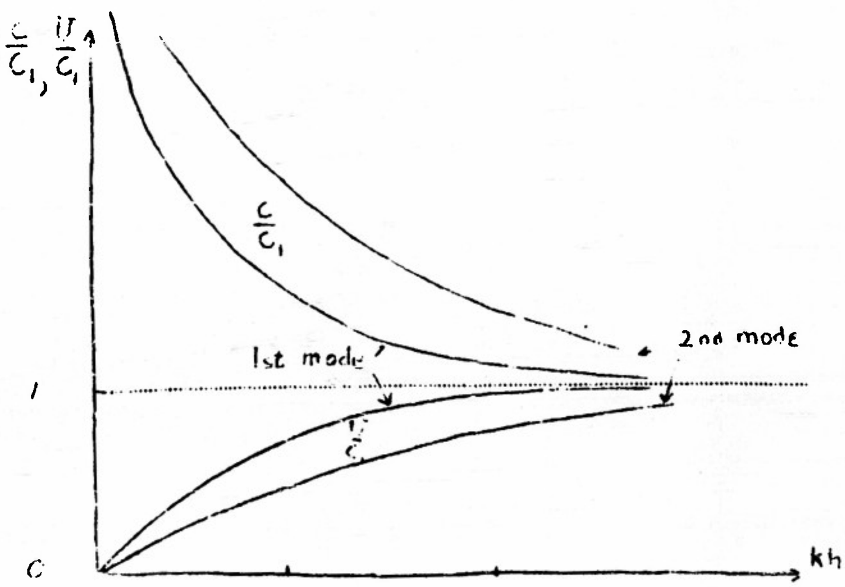
I. The Normal Mode Theory of Sound Propagation

The normal mode theory of sound propagation in layered liquids is an extension of the concept of normal modes of vibration in enclosed spaces (standing waves) to the case of spaces that are unbounded in some direction or set of directions (traveling waves). To use an analogy due to Pekeris a fluid-filled parallelepiped such as a room full of air is characterized by an infinite set of well defined characteristic acoustical frequencies. If the walls of this room be expanded indefinitely, we have a space of infinite extent in all horizontal directions bounded by two horizontal planes (floor and ceiling). This space is still characterized by an infinity of characteristic frequencies or modes which are now propagating modes. In other words, the energy radiated by a source within the prescribed boundaries is no longer constricted to remain within a given volume, but will travel outwards to infinity and dissipate itself in all horizontal directions.

II. The Perfect Acoustical Wave Guide

If this fluid layer is bounded by perfectly reflecting media, i.e. if the wall and ceiling of our expanded room are infinitely rigid, all of the energy produced by a source of sound in it remains

within it, and we have the so called perfect acoustic wave-guide. The propagation of this acoustical energy is dispersive, i.e. the velocity of propagation depends upon the frequency, and one must distinguish between phase velocity and group velocity. The <u>phase velocity</u> may be defined as the instantaneous velocity of a point of given phase in the horizontal direction (such as a wave crest). The <u>group velocity</u> is the velocity with which energy propagates in this direction. Each normal mode of propagation is characterized by its own set of phase and group velocity curves (Fig 1.).



<u>Figure 1 Dispersion Curves for Perfect Wave Guide</u>

$k = \frac{2\pi}{\lambda}$, λ being the wave length, k is the wave number
c_1 is the speed of sound in the layer
c is the phase velocity along the layer
U is the group velocity
h is the thickness of the layer

In this perfect wave guide, the group velocity tends to zero for infinitely long wave lengths, and the phase velocity tends to infinity. This corresponds to normal incidence, i.e. to waves bouncing back and forth normally from the two walls. Since no energy travels laterally under these conditions the group velocity is zero.

III. The Imperfect Acoustical Wave Guide

Pekeris has dealt extensively with the case in which the fluid layer overlies a fluid body of higher sound velocity, the upper surface of the layer being free. His well known work on the subject was intended to represent a layer of water over unconsolidated or semi-consolidated sediments. In this case, if a point source be located within the layer, only the energy in a certain solid angle (corresponding to angles of incidence greater than the critical angle at the bottom) remains trapped inside the layer. The rest is leaked off since upon each reflection at this lower boundary a certain fraction of the incident energy gets transmitted and lost into the underlying medium. At large distances from the source, the recorded disturbance is thus due almost exclusively to the energy contained within the cone of total reflection: this corresponds to the undamped normal modes of propagation.

Since only part of the energy produced by a source in the layer remains completely trapped within it, this situation may be called an imperfect wave guide.

The existence of a critical angle corresponds to a cut off for long wave lengths. Wave lengths greater than these are attenuated because they correspond to angles of incidence less than critical. For water 50 feet deep and a sediment velocity of 6000 ft/sec the corresponding low frequency cut-off for the fundamental mode would be of the order of 45 cps.

It is clear that normal incidence cannot be attained without resulting in attenuation of the propagating wave system, so that a zero group velocity is never achieved. The group and phase velocity curves for the first mode are sketched in Fig 2. As in the perfect wave guide, the group and phase velocities tend to the speed of sound in the water-layer for high frequencies (large kh). For decreasing k, the group velocity U starts downwards, reaches a minimum, and then starts up again until it reaches the cut-off corresponding to $c = U = c_2$ (this point corresponds to the ground wave or so called "refracted wave").

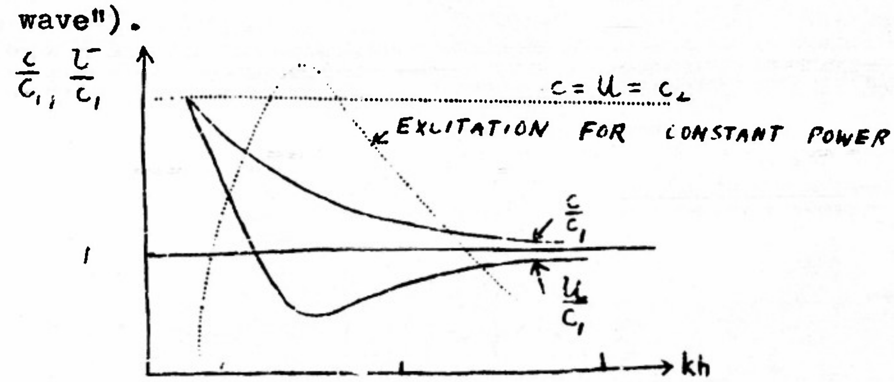


Figure 2.

$k = \frac{2\pi}{\lambda}$
h is the thickness of water layer
c_1 is the speed of sound in water
c_2 is the speed of sound in the sedimentary bottom
c is the phase velocity
U is the group velocity

This minimum group velocity has been called the Airy phase. The higher modes of propagation are also characterized by Airy phases.

When the high velocity sediment underlying the water is itself compounded of layers of different acoustical properties, the group velocity curves are more complicated in character and each mode will in general be characterized by several minima and maxima (which we may still call Airy phases). The values of the group and phase velocities, as well as the frequencies corresponding to these Airy phases, depend upon all the parameters involved (thickness, sound velocities and densities).

IV. Properties of the Airy phase

The best known phenomenon associated with the Airy phase, one that has been pointed out and investigated by a number of authors in the scientific literature is its selective effect: if an impulsive point source be used to excite the medium, the frequencies associated with the vicinity of the Airy phase arrive last and form a prominent wave packet that becomes one of the outstanding features on any record made at a sufficient distance from the source. In other words, if the water-sediment acoustical system be likened to a filter, the Airy phase frequency corresponds to a resonant frequency of the filter. This feature has received abundant experimental verification both in shallow water explosion work and in earthquake studies.

This filter analogy suggests a second property of the Airy phase frequency which can be verified mathematically: if the frequency of a simple harmonic source in the medium be varied continuously, maximum excitation amplitudes will be obtained near the Airy phase frequency, exactly as in the case of a filter, the lowest impedance is secured for a resonant frequency. This phenomenon does not appear to have been investigated experimentally. It gets more pronounced as the sound velocity c_2 of the bottom increases.

In Fig 2, we have made a rough sketch of the amplitude at a given range as a function of the k at the source $k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$, f being the frequency in cps . Figures 3 and 4 give the relative pressure amplitudes for a constant power simple harmonic point source as a function of source frequency.

V. Practical Applications of the Airy phase.

These two important properties of the Airy phase suggest several practical applications:

1. In constant frequency work, it should be possible to exploit the relatively higher excitation amplitudes near the Airy phase frequency for low frequency ranging purposes. By using this frequency in a given location one should be able to:

   a) increase the effective ranging distance

   b) secure greater legibility of records at shorter ranges

As mentioned above this phenomenon should be most striking for high speed bottoms.

We believe that the investigation of this effect should be included as soon as possible in our shallow water program. This would of course necessitate the use of continuously variable frequency sound sources covering a broad range (30 to 300 cps).

2. In other types of shallow water work such as the detection of ship noises it might prove useful to be able to peak listening devices at the Airy frequency proper to a given location. In any event it clearly emphasizes caution in interpreting relative strengths of spectral lines in different oceanographic regions. As an example low frequencies below the cut off frequency for the two layered case may propagate as undamped modes in a multi-layered case. A hydrophone about half-way down the 2nd layer might be more sensitive to these frequencies.

3. The frequency, phase and group velocities of the Airy phase depend upon the water depth, densities and sound velocities of the various layers involved.

An earlier memorandum points out the importance of determining sedimentary thicknesses and velocities in connection with any comprehensive low frequency shallow water program. It was stated therein that the most efficient method of determining these quantities would

be to institute a refraction profile sub-program as part of our shallow water investigations. A simultaneous investigation of the Airy phase produced by explosions (which incidentally, would not involve the use of any additional equipment) would provide:

a) an independent check upon the refraction data

b) an estimate of the sedimentary densities, resulting in an unambiguous determination of bottom reflectivity

c) a direct measure of the optimum frequency (in the sense of paragraphs V 1 and 2) and of the associated group velocity.

VI. Numerical Program

The interpretation and most efficient application of the above principles (especially V paragraph 3) would be contingent upon the calculation of tables describing the dispersive properties of most two, three and four layer cases likely to be encountered in the field. These computations are perfectly straightforward and routine but quite lengthy. A several months long computing program is thus urgently needed to complement our understanding of low frequency sound propagation in shallow water.

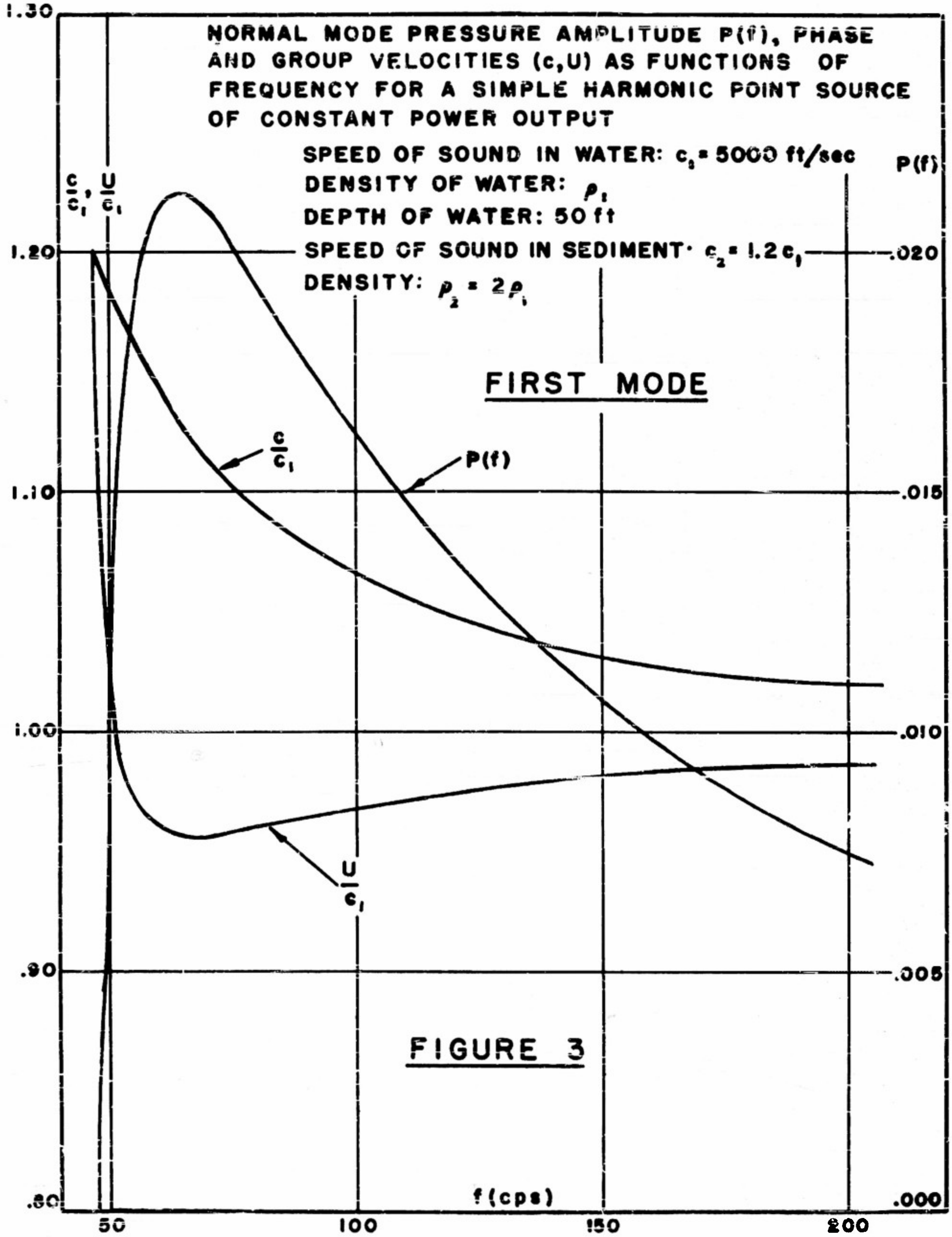

NORMAL MODE PRESSURE AMPLITUDE P(f), PHASE AND GROUP VELOCITIES (c,U) AS FUNCTIONS OF FREQUENCY FOR A SIMPLE HARMONIC POINT SOURCE OF CONSTANT POWER OUTPUT
SPEED OF SOUND IN WATER: c_1 = 5000 ft/sec
DENSITY OF WATER: ρ_1
DEPTH OF WATER: 50 ft
SPEED OF SOUND IN SEDIMENT: c_2 = 1.2 c_1
DENSITY: ρ_2 = 2 ρ_1
FIRST MODE
$\frac{c}{c_1}$, $\frac{U}{c_1}$
P(f)
$\frac{c}{c_1}$
$\frac{U}{c_1}$
1.30
1.20
1.10
1.00
.90
.80
.020
.015
.010
.005
.000
f(cps)
50
100
150
200

FIGURE 3

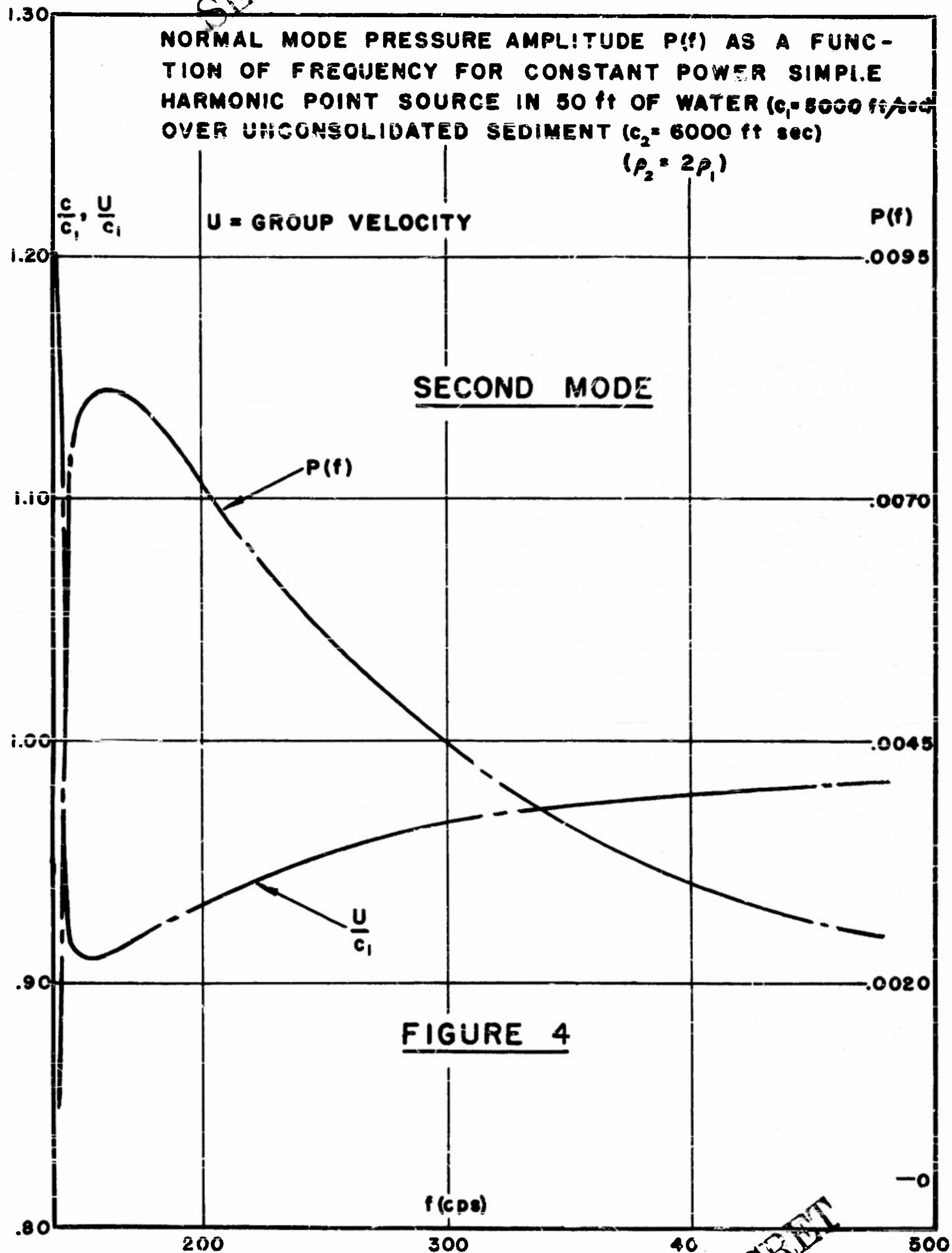

NORMAL MODE PRESSURE AMPLITUDE P(f) AS A FUNCTION OF FREQUENCY FOR CONSTANT POWER SIMPLE HARMONIC POINT SOURCE IN 50 ft OF WATER (c_1= 5000 ft/sec) OVER UNCONSOLIDATED SEDIMENT (c_2= 6000 ft sec) ($\rho_2 = 2\rho_1$)
$\frac{c}{c_1}$, $\frac{U}{c_1}$
U = GROUP VELOCITY
P(f)
SECOND MODE
P(f)
$\frac{U}{c_1}$
1.30
1.20
1.10
1.00
.90
.80
.0095
.0070
.0045
.0020
0
f (cps)
200
300
400
500

FIGURE 4

COLUMBIA UNIVERSITY

Hudson Laboratories

Dobbs Ferry, N. Y.

PROJECT MICHAEL

Contract N6-ONR-27135

Technical Memorandum to File No.11

The Use of the Surface Sound Channel in Shallow Water Listening

by

R. A. Frosch

W. A. Nierenberg
Director

Research Sponsored by
Office of Naval Research

CONFIDENTIAL — November 24, 1953

SECURITY INFORMATION — Copy No.

This report consists of 5 pages

THE USE OF THE SURFACE SOUND CHANNEL IN SHALLOW WATER LISTENING

by

R. A. Frosch

INTRODUCTION

It may be possible to utilize the surface sound channel, when it exists, to improve the performance of systems for the passive and active detection of submarines and ships in shallow and moderate depth water. As will be seen below, such a system would require considerable flexibility of frequency of operation, and for greatest efficiency would require frequent collection of hydrographic information in the operational waters.

Surface Sound Channel Transmission

In winter in many localities (e.g., New York Bight), the customary heavy weather and high winds produce mixing of the surface water. This mixing may frequently extend to a depth of several hundred feet or to the bottom in regions of moderate depth. Such a mixed layer has a sound velocity which increases with depth due to the increase of pressure with depth. The gradient is of the order of .02/sec. In such a region sound of appropriate frequencies is propagated with negligible leakage from the duct.

Voorhis of Woods Hole Oceanographic Institution[1] has presented an analysis of this effect based on a variety of sources. He gives curves for the attenuation of sound due to leakage from the surface duct: for example, 1 kc sound traveling in a surface isothermal duct 150 to 200 feet deep would have a leakage attenuation of .1 db/kiloyard. The exact isothermal duct depth corresponding to this leakage depends on the precise thermocline conditions below the isothermal layer. The actual attenuation of the sound in such a duct is determined, in addition to the leakage effect, by two other factors: scattering from the surface and real volume absorption of the sound.

The effect of scattering from the surface is difficult to estimate precisely, but would probably be relatively minor for reasonably low frequencies ($<$ several kc) and deep channels ($>$ 50 feet). This effect would depend of course on sea and swell state, and could be investigated.

Absorption of sound in the region of frequency up to 20 kc can be approximately represented by the formula

$$.01 \ f^2 \text{ db/kyd}$$

with f in kc. Combination of this absorption with the leakage attenuation, using duct thickness as a parameter, produces curves of attenuation vs frequency for each transmission mode which have pronounced minima (see Table I). The existence of these minima has been verified by Officer of WHOI[2].

The effect of ocean bottom closely underlying an isothermal duct would be to increase the sound intensity in the duct, due to partial reflection of sound from the bottom.

Use of the Duct Transmission

Suitable choice of frequency for particular conditions of water might well lead to good active and passive ranges, particularly if used with suitable filters. In the passive case, for example, it might be well to listen through filters whose shapes were the inverse of the duct attenuation curves.

Seasonal Effects

Efficient use of these ducts would require constant knowledge of an adjustment for the particular conditions prevailing at the time of use. In general this transmission would be efficient only during the winter months when the isothermal layers and positive sound velocity gradients exist. At other times of the year, and particularly during the summer, the gradients may be negative.[3] Under these conditions transmission would be expected to be very poor as the sound would be funneled into the bottom by the velocity structure of the water. This is probably the explanation of the seasonal variability of performance of the prewar Coast Artillery binaural ranging station at Sea Bright, New Jersey.[4,5]

TABLE I

Duct Thickness	Frequency of min. attenuation	Attenuation at min.
50 ft	6300 cps	0.54 db/kyd
100 ft	2800 cps	0.09 db/kyd
200 ft	1200 cps	0.015 db/kyd

REFERENCES

1. Sound Transmission in the Surface Isothermal Channel Part I - An Application of Normal Mode Theory, by Arthur Voorhis. Woods Hole Oceanographic Institution Reference No. 52-90. November, 1952.

2. Sound Transmission in the Surface Isothermal Channel Part II - Experimental Measurements, by Charles B. Officer, Jr. Woods Hole Oceanographic Institution Reference No. 53-18. March, 1953.

3. The Oceanography of the New York Bight, by B. H. Ketchum, A. C. Redfield, and J. C. Ayers. Papers in Physical Oceanography and Meteorology, Published by Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, Vol. 12, No. 1, 1951.

4. Modified Rotating Beam Installation (Subaqueous Sound Ranging). Proceedings of the Coast Artillery Board, Project No. 993. January 3, 1935.

5. Ocean Temperatures Off New York Harbor, Narragansett Bay, and Boston, during March-June, 1942, and Their Relation to Underwater Sound Ranging, by R. B. Montgomery. Signal Corps General Development Laboratory Engineering Report No. C-2. August 22, 1942.